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SMOKE DYNAMICS OF SOLID ROCKET PLUMES

FINAL REPORT

Eugene Miller, Professor of Chemical Engineering

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Secondary smoke, contrails, light attenuation, turbulence, rocket propulsion, rocket plumes, condensation nuclei.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The formation of secondary smoke in a solid rocket plume and the attenuation of a laser signal through it have been modelled by codes DROP-4 and OSA-4. Condensation nuclei have been characterized and number and size distribution measured from data obtained in the U. S. Army Missile Command's Smoke Characterization Facility. Predictions from DROP-4 and OSA-4 compare satisfactorily with experimental flight data.

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Statement of Problem Studied: Solid rocket plumes contain significant quantities of condensible gases such as water, hydrogen chloride and hydrogen fluoride. Smoke may develop anywhere in the plume in the form of droplets where the thermodynamic requirements of temperature and concentration are met. This smoke is termed secondary smoke to differentiate it from the primary smoke found in the plume in the form of particles of alumina, other metal oxides, carbon, liner debris etc. For so-called smokeless propellants, secondary smoke is a primary cause of visibility of the rocket and of signal attenuation of optical guidance systems. The task undertaken here was to define the physical and chemical factors involved in the dynamic formation of secondary smoke in the rocket plume, to model its formation as a function of radial and axial position in the plume and to model the laser attenuation through a smoky plume for typical plume and laser geometries.

Summary of Most Important Results: (1) The basic equations of heat, mass and momentum transfer of smoke formation in a rocket plume were written including factors of turbulence, non-continuum, non-equilibrium and Kelvin surface tension effects. The velocity, temperature and concentration profiles in the plume itself were modelled using existing codes. These were all combined in a computer code with an acronym DROP 4 which predicts the number, size distribution and chemical composition of secondary smoke droplets as a function of radial and axial position in the plume.

(2) The laser attenuation through the rocket plume was modelled from single-light scattering theory using the DROP 4 output for any desired angular light vector and any offset from the plume centerline. The effects of primary smoke from smokeless propellants were also included. The signal attenuation computational code was given the acronym OSA 4.

(3) In order to describe secondary smoke by DROP 4/OSA4 information is needed concerning condensation nuclei on which the smoke forms. From theoretical

considerations and data obtained at the U. S. Army Missile Command's Smoke Characterization Facility (SCF) the number and size distribution of the nuclei were determined. It was also concluded that the nuclei were predominently heterogeneous in nature. A computer program BEER 4, was written for routine extraction of the nuclei count from multispectral optical measurements in the SCF. The definition of the thermodynamic dewpoint conditions of secondary smoke for typical solid propellants in the SCF was made by means of the code SMOKE.

(4) The DROP 4/OSA 4 codes were used to describe the secondary smoke and the laser signal attenuation for a series of prototype rocket flights and comparisons were made with experimental data. It was found that the existing plume codes do not correctly predict the temperature and mass concentration profiles in the outer portion of the plume boundary layer where secondary smoke forms. After modifying the profiles to permit thermodynamically the formation of secondary smoke, it was found that DROP 4/OSA 4 satisfactorily predict the laser signal attenuation in actual rocket flights. Using multispectral signal attenuation measurements to extract average droplet size and concentration information from flight data good agreement was found with the predictions made by DROP 4.

List of Publications

(1) "The Dynamics of Secondary Smoke Generation in Smokeless Solid Rocket Plumes." 1975 JANNAF Propulsion Meeting, (October 1975) JANNAF Propulsion Meeting, (October 1975).

(2) "Alumina Particle Velocity and Temperature in a Solid Rocket Plume." AIAA Journal B, No. 12, 1668-1670. (December 1975).

(3) "The Prediction of Secondary Smoke in Solid Rocket Plumes." 1976 JANNAF Propulsion Meeting (December 1976).

(4) "The Dynamics of Secondary Smoke Generation in Smokeless Solid Rocket Plumes." 12th International Symposium on Space Science and Technology, Tokyo (1977).

(5) "The Modelling of Secondary Smoke in Solid Rocket Plumes." 1978 JANNAF Propulsion Meeting (January 1978).

(6) "Propellant Smoke Particle Size Distribution and Concentration Measurements and Their Correlation with Condensation Nuclei Theory," with L. B. Thorn, S. Smith, J. W. Connaughton, J. A. Murfree and W. W. Wharton of U. S. Army Missile Command, 1979 JANNAF Propulsion Meeting (February 1979).

(7) "Measured and Predicted Laser Signal ATtenuation Through a Solid Rocket Plume," with J. W. Connaughton and L. B. THorn of U. S. Army Missile Command. 1980 JANNAF Propulsion Meeting (March 1980).

(8) "Prediction of Secondary Smoke and Optical Signal Attenuation in Solid Rocket Plumes." 12th JANNAF Plume Technology Meeting (November 1980)

(9) "Comparison of Experimental and Predicted Secondary Smoke Optical Signal Attenuation." 13th JANNAF Plume Technology Meeting (April 1982).

(10) "Smokeless Propellants; Fundamentals of Combustion of Solid Propellants" ed by K. K. Kuo and M. Summerfield. AIAA Progress in Astronautics and Aeronautics. In press.

Participating Scientific Personnel

Eugene Miller